Synergy of Combining Microfabrication Technologies in Orbit

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Abstract

The free vacuum in orbit makes it an ideal place for many microfabrication processes. Much current research has concentrated on orbital fabrication of single high vacuum processes, such as Wakeshield's silicon epitaxial growth. Yet, even the simplest semiconductor devices require the combination of many microfabrication steps, such as thin film deposition, patterning (photolithography), and etching. Fortunately, with the right choice of processes, the advantage of the native vacuum greatly reduces the number of microfabrication process steps, and equipment complexity, mass and power requirements. The key to this synergy is the modification of the processes that use abundant earth based resources (water, power), to those better suited to the vacuum and microgravity space environment. We have investigated a wide range of microfabrication processes for orbital environmental compatabilty. Many types of deposition (plasma sputtering, CVD, ion implant) and etching processes (Plasma, RIE) require base vacuum levels $>10^{-7}$ torr, above that of LEO. Compared to earth operations, removal of the vacuum systems from orbital equipment leads to reductions estimated for each process in equipment mass (48-72%), volume (37-59%), process consumable supplies, and equipment life cycle maintenance.. To create true structures, an important simplifying step is the introduction of a vacuum based process inorganic resist for photolithographic patterning of films. Since the orbital vacuum also removes earth based contamination from the wafer environment, the elimination of organic resists almost eliminates local contamination thus reducing interprocess cleaning steps, which consume large quanities of water, acids and organic solvents. It also increases throughput and improves film/etching quality. The adding vacuum based plasma/ion cleaning processes further eliminates liquid consumables. The result is a synergistic orbital based methodology for deposition, patterning, and etching that is capable of building microfabricated structures. This is leading to studies of an orbital microfabrication satellite.

1 Introduction

Microfabrication is the science of modifying, growing or depositing thin layers of materials, typically on semiconductor substrates, and patterning those films into precise structures. The repeated application of these processes creates devices ranging from simple solar cells and sensors to complex microchips. What makes this technology important for application in space is the fact that many of the microfabrication deposition and etching processes require base vacuum levels >10^{-7} torr, above that of Low Earth Orbit. Thus the free vacuum in orbit, with pressures <10^{-8} torr, makes it an ideal place for many such microfabrication processes.

Much current research has concentrated on orbital fabrication of single high vacuum processes, such as Wakeshield's[1] silicon epitaxial growth or layer deposition. While this deposition is a very expensive process to do on earth, it is just a beginning process for a select group of microchips. Yet, even the simplest semiconductor devices or sensors require the combination of many microfabrication steps, especially that of thin layer deposition, photolithography which then defines the layer into the desired pattern, and etching which shapes the material creating microstructures. Furthermore researchers testing deposition processes find that patterned test structures are often necessary to measure import material parameters, such as film thickness uniformity, resistivity, dielectric strength, adhesion and conformality. This is especially true in the case of metal films where optical techniques cannot be used. Thus the key to careful control of microfabrication processes is to create and measure such structures soon after deposition.

Space based microchip manufacturing has been suggested previously[2], but that preliminary study indicated research was needed in several areas. Standard earth fabrication techniques are difficult to transfer into the microgravity and vacuum environment of LEO They are optimized to make use of resources like water, power, air pressure and gravity that are plentiful on earth. Fortunately, with the right choice of processes, the advantage of plentiful clean native vacuum greatly reduces the number of microfabrication process steps, and equipment complexity, mass and power requirements. This paper outlines how to use the available vacuum environment in an alternative set of microfabrication processes that could replace the standard processes, with significant savings in equipment size, mass and consumables. More importantly this modified processes removes significant sources of contaminates which in turn removes many other process steps. A computer model has been developed that compares the standard earth base processes consumables with proposed vacuum based ones resulting in a process flow that is optimized for orbital facilities. The result is a synergistic orbital based methodology for deposition, patterning, and etching that is capable of building microfabricated structures.

2 Standard Earth Based Microfabrication Process Flow

Now, consider the basic processes of microfabrication as currently practised on earth[3]. This section will give a simplified outline of the processes steps, with a emphases on thr areas where space application makes important changes. First note the cleanliness requirements: advanced modern microfabrication necessitate the processes be performed in "Class 1 clean rooms" which must filter their air to contain less than 1 particle per cubic foot of a diameter < 0.1 micrometers. The rooms are positively pressurized to prevent outside air from leaking into them bringing contaminants from the outside world. Workers in those facilities already wear clothing that looks like space suits, preventing any contamination of the processing environment by their skin or hair. These clean suits have helmets that filters the air they exhale before allowing it to enter the room. Significant amounts of power is consumed just filtering and moving that clean air through the facility in order to keep the outside dirt away from the processes. Note this important point: on earth microfabs must fight hard to prevent contamination from the native environment; in space the background vacuum is cleaner that the cleanest earthly lab.

Starting material for microfabrication is usually a silicon wafer, a flat thin disk or another substrate, typically 6-12 inches (150-300 mm) in diameter by 0.5-0.6 mm thick. Microfabricated devices are created by the deposition and patterning of typically 4 -30 layers of thin films on these substrates. The very first process step at any layer is an intensive cleaning, such as the RCA clean (see Table 1 for the full process flow). Note the RCA clean consists of 3 major heated ($80^{o}C$) etching baths to remove organics and metal contaminants, with each bath followed by several minutes of cleaning in flowing deionized water (water purified to 15 megaohm cm resistivity in a complex filtration system). Note that the RCA clean described here is just typical, some layers required different, but similarly complicated liquid cleans. Care in these steps is absolutely necessary to obtain good results when depositing one layer on another. What is seldom realized is that a single layer's RCA cleaning steps consume nearly 80 kg of wafer, and significant power cleaning and heating the baths (see section 4). While such cleans may be simplified for depositing only a single layer of material, they are needed in any multilayer process and are critical in the quality of the films deposited.

Table 1- Standard Earth Based Single Layer Microfabrication Process Flow

No.	Step Name	Materials	Time (sec)
1	RCA organic clean	DI water, NH_4OH, H_2O_2 at $80^{o}C$	600
2	DI water rinse	Flowing DI water rinse	120
3	HF oxide removal	DI water and HF	30
4	DI water rinse	Flowing DI water rinse	120
5	RCA metal clean	DI water, HCl, H_2O_2 at $80^{o}C$	600
6	DI water rinse	Flowing DI water rinse	900
7	Deposit or grow layer	eg sputter deposit Al layer	2000
8	Photoresist application	Spin on photoresist	20
9	Photoresist soft bake to harden	$100^{o}C$ in bake oven	1200
10	Expose photoresist	UV projection of pattern	85
11	Develop photoresist	Organic solvent developer	20
12	Photoresist hard bake to harden	$120^{o}C$ in bake oven	1200
13	Etch deposited layer	eg Plasma etch Al layer	922
14	Strip Photoresist	O Plasma strip & organic solvent	174
15	DI rinse	Flowing DI water	300

After cleaning typically comes a thin film deposition or oxide growth (see Figure 1A). Oxides are grown by exposing the wafer to oxygen or steam in a furnace at $1000\text{-}1150^{o}C$ for times of few minutes to hours. Metals such as aluminum alloy or other inorganics are deposited via sputtering by bombarding a target material with accelerated argon ions (at pressures of a few millitorr), which knock off the atoms of the material and deposit them onto the wafer surface. The quality of the deposited film is critically dependent on any oxygen or contaminants present in the chamber that may interact with the depositing atoms or the surface of the wafer while the film is being formed and hence the chamber is typically pumped down to at $<10^{-7}$torr before operation. Chemical Vapour Deposition (CVD) methods are where two typically gaseous chemicals are reacted at low pressures (or by using RF plasmas to enhance the reactions), again with pressures in the few millitorr range, and pump downs to lower pressures to obtain good quality films. Layer thicknesses vary from tens of nanometers to a few microns.

Then this layer is patterned using photolithographic definition, where a thin (about 1 micron) coating of an organic light sensitive material called photoresist is carefully laid down: resist film quality is import for good definition. Photoresist films are obtained by depositing or spraying a wafer with liquid resist and spinning it up to about 4000 rpm so that interaction of rotational, gravity forces, surface tension and viscosity creates a controlled thickness of resist. The film is then baked to remove solvents. A UV image of the desired pattern is optically projected onto the surface (see Figure 1B). When developed in a wet solvent bath the resist is left in the unexposed area, while the exposed region has the resist removed from it (Figure 1C), and baked dry.

Etching of thin films removes the pattern areas that are not protected by the resist (Figure 1D). While originally wet chemical acid etches were used this has been replaced by dry processes. Dry etching all involve good vacuums that are modified for the etching process. Common methods are ion milling (where atoms of argon bombard the film and knock of the surface atoms a few at a time), reactive ion etching (where specific ions react chemically with the film to remove it), and plasma etching (where a cloud of ionized gas reacts chemically with the film). All involve pumping the systems to ~10^{-7} torr and back filling with gases to a few millitorr pressures. In each case the presence of small contaminants can significantly affect the uniformity of the etching processes and the quality of the surface left behind.

The photoresist is then stripped (often in an oxygen plasma etcher - see Figure 1E). However it is very hard to remove all the organics added by the resist, and there is always the danger of other outside contaminants. Hence the RCA clean at the beginning of each step is need to remove these. This combination of steps here: cleans, deposition or growth of a layer, photolithographic definition, etching and resist stripping is repeated for each layer and pattern to make the final circuit of even the simplest device.

Note that the times listed in Table 1 are just the time for each process step and do not include the transport between steps. Also note several of the steps are applied to many wafers at a time, so an average time per wafer needs to be considered.

The problem with space microfabrication is that many of the wet processes are very hard to apply in the vacuum and microgravity environment of space. The cleanings involve huge quantities of materials, many difficult to handle in microgravity. The solvents are quite volatile, presenting problems for local contamination. Even the depositing of the photoresist on the wafer creates a problem as it involves gravity and air pressure to work as done on earth. More importantly the photoresist's constant contamination of the wafers actual removes many of the advantage of the clean vacuum environment. The solution is to switch to a resist that is deposited with a vacuum based process.

3 Dry Vacuum Based Photolithography

To take advantage of the ultra clean environment of the native space vacuum, which introduces less contamination that even the best earthly cleanrooms, the current photoresist process must be changed. While organic based photoresists are used in microfabrication now they present problems as microfabrication photolithography moves from the current exposures of 248 nm UV to future generations of 193 nm or 150 nm. At those short wavelengths current organic resists have trouble operating Furthermore the contamination caused by the organics is something that creates a constant problem. This has lead to studies of inorganic based resists. The problem is that while there are optically sensitive inorganics they often involve materials, such as silver or copper, that destroy transistor operations.

However modern photolithography exposure systems use Eximer lasers as the light source. Hence rather than a steady UV exposure the wafers are subjected to pulses of high power light (typically 10 mJ/sq cm). At these powers significant heat is induced by optical absorption in thin inorganic films creating thermally induced phase changes. Several researchers, including the author, have been investigating the concepts of inorganic thermal vacuum resist Typically the films are deposited and developed using vacuum based processes and hence are Dry resists.

One established process that is available from the literature, developed at M.I.T. Lincoln Lab, illustrates many of the features of these dry resists[4-5]. As Figure 2 shows the resist consists of a thin 30 nm film of AlO_x cermets deposited by evaporation or sputtering of aluminum films in the presence of oxygen at $2\text{-}5\times10^{-6}$ torr pressure. The AlO_x is deposited on top of a CVD or sputter deposited Carbon film 1 micron thick. Exposed to UV Eximer laser pulses of 40-100 mJ/sq cm converts the AlO_x into another aluminum oxide phase (Black Aluminum). The films are then etched with a Reactive Ion Etching in CHF_4. An important part of any resist process is the ability to strip the resist and have it resistive to the etching of the layers below. To do this the developed AlO_x films themselves act as a mask for an oxygen plasma etching of the Carbon. Since oxygen plasma is not used for microfabrication processes except in the case of organic films the carbon provides a thick layer that is only slowly eroded by other etch gases used. This process has been proved to have a resolution as good as modern resists.

While the original researchers did not specify this, an important part of any workable resist process is the ability to strip the resist. We have added two processes that will work for this. First fully UV expose the wafer and etch the fully converted AlO_x with the RIE etch. Alternatively ion mill the AlO_x or develop another RIE etch that removes unconverted films. As the patterned layers below are seldom the 30 nm thickness of the AlO_x this should have a small effect on the etching processes. Then oxygen plasma will strip the carbon leaving no residue.

The one downside of the AlO_x resist is that it takes a much higher exposure UV energy; 5-10 times that of organic resists. This is an important problem for earth based processing as it significantly slows down the process flows through the exposure systems. However for experimental space based work that is not a significant disadvantage. The authors are developing an alternative inorganic thermal film to replace the AlO_x which should be as sensitive as current resists but retain the advantages of the cermets. However to use processes that are available in the literature the AlO_x form has been used in the rest of this paper.

Table 2 now outlines the process flow for a dry vacuum resist process. On earth there would be concerns that new organics, which are continually introduced into the clean room, might contaminate the process. The only way to avoid that was to keep the samples always in a vacuum environment. In space effectively the only significant contaminates are those imported to the local station environment. Thus provided the samples are kept in vacuum the process as outlined should be effective in keeping the wafers clean.

Table 2 – Space Based Dry Resist Single Layer Microfabrication Process Flow

No.	Step Name	Materials	Time (sec)
1	Deposit or grow layer	e.g. sputter deposit Al layer	370
2	CVD deposit C protection layer	Carbon	2000
3	Sputter deposit AlO_x	Argon and O in sputter system	240
4	Expose AlO_x	UV projection of pattern	72
5	Etch AlO_x	Reactive Ion Etching in CHF_4	5
6	Etch C protection layer	O_2 plasma	120
7	Expose and remove AlO_x	Ion milling	23
8	Etch deposited layer	e.g. Plasma etch Al layer	120
9	Strip C layer	O_2 plasma	173

4.Modeling the Advantage of Dry Resist Processing in Space

To obtain the gains from this dry process we have created a computer model which includes every step of every fabrication processes, and the equipment required for it. The model uses typical microfabrication process consumables (materials) and equipment for every step. Typical earth based equipment, including their vacuum pumps, are included with their volume, mass, process times, power consumed etc. In the case of vacuum pumps equations were created that give the pumping rate and power versus chamber pressures. These vacuum pump power consumptions were then compared to measured values on existing pumping systems with good agreement. Items such as liquid/gas flows and solid usages were used to calculate the consumables at each process level. Process times were calculated both on the process times and the time taken to load/unload samples.

Table 3 - Equipment Mass and Volume Reductions in Space

	Earth Based		**Space Based**			
Equipment	**Mass**	**Volume**	**Mass**	**Volume**	**Mass**	**Volume**
	(kg)	**(m^3)**	**(%)**	**(%)**	**(kg)**	**(m^3)**
INTERPROCESS CONVEYOR	50	0.1	75%	75%	37.50	0.075
WETBENCH	500	4	56%	65%	277.50	2.58
FURNACE	500	2.88	49%	67%	245.00	1.9296
PHOTORESIST SYSTEM	300	0.8	49%	58%	147.00	0.464
LITHOGRAPHY DSW 193	500	5	52%	57%	261.25	2.8375
DEVELOP SYSTEM	300	0.8	46%	64%	137.25	0.51
PLASMA ETCHER	300	0.64	28%	51%	84.75	0.3248
ASHER	500	1.92	32%	41%	157.50	0.7776
ION IMPLANTER	1000	20	33%	42%	325.00	8.3
PLASMA CVD SYSTEM	300	0.64	28%	51%	84.75	0.3248
SPUTTER SYSTEM	500	4	28%	51%	141.25	2.03
RTP_SYSTEM	500	4	46%	68%	228.75	2.73

For orbital-based process the vacuum pumps were then removed from the system, processes that involve pump down steps eliminated, and the chamber wall sizes reduced to represent the much smaller pressure differential now experienced. Table 3 gives for typical microfabrication equipment the resulting reduction in mass, and volume for a space based system. Note the typical reductions range from 48-72% in mass and 37-59% in volume. One assumption made here is that it would not be necessary to continuously gas flows through systems in orbit as is done on earth. Unlike space systems, atmospheric gases constantly leak into ground based vacuum chambers, requiring continuous pumping to remove contaminates, and hence nonstop process gas flows to keep the right mix of process gases/plasmas. However this must be proved in future testing.

The model thus lets us assemble complete process flows easily for multilayer structures. It gives power, mass of each type of materials, power consumed and its origins, and process times. These values were then summarized in charts for each process step. The model's results for larger complicated full CMOS processes are in reasonable agreement with published figures by SEMITECH[6] in both power, time and consumables, especially water.

To compare earth and space based processes using the model a simple 3 layer process flow was constructed. This consists of a first level oxidation that was patterned and etched. An aluminum metal layer was then deposited, patterned and etched. Then a top level of CVD oxide was deposited patterned and etched. This would be a simple test structure.

Figure 3 compares the incremental material mass consumption for both wet and dry processes, broken down by solids, liquids and gases. In earth based processes almost all the mass consumed is that in the cleaning process and takes a combined 180 Kg for the 3 levels. In space it is really the layer deposition materials and dry resists that are the consumables, with only 0.00084 Kg used for the structure. This gives a reduction in consumables mass to 0.00047% of the earth based process.

Figure 4 compares the incremental power usage for both wet and dry processes, broken down by were the energy is expended (heating the wafer, depositing material, operating equipment or vacuum pumps). In earth based processes almost all the power consumed is in heating the fluids in the cleaning process. The total is a combined 47.2 MJ for the 3 levels. Indeed this power consumption works out to an average of 4.37 Kwh per level which is in agreement with typical earth from the SEMITECH roadmap report[6]. In space the process energy to deposit the layer materials and dry resists dominates, totaling 1.6 MJ used to make the structure. This is a power reduction to 3.36% of the earth based process or only 0.15 Kwh per level. Since power supplies are expensive in space this is an important reduction.

Figure 5 compares the process time used for both wet and dry processes, broken down by doping, vacuum pressure changes, etching, patterning, thermal heating, depositon, cleaning, and wafer transport. In earth based processes much of the time is consumed in cleaning and thermal processes connected with depositing the photoresist films, taking a combined 12.3 hours for the 3 levels. In space it would be really the layer deposition of materials and dry resists that dominates, and this takes only 4.5 hours to build the structure. This gives a time reduction to 37.1% of the earth based process.

The important results of the material mass and power savings is that a Dry resist process changes space based microfabrication of multiplayer structures from a very expensive process that requires many consumables to one that is possible for both experimental and production purposes. It is the synergist saving that comes from the choice of fully vacuum based processes that make this possible

5 Conclusion and Future Verification of the Space Based Microfabrication

By switching to a Dry resist process a synergistic orbital based methodology for deposition, patterning, and etching has been proposed which is capable of building microfabricated structures. This is leading to studies of ISS based research on the creation of simple test structures or sensors and of an orbital microfabrication satellite.

While the computer models give interesting results it is important that process flow and equipment be verified on earth. The individual processes can be tested in the regular vacuum chambers. Testing of the complete process flow and equipment is possible using Boeing's large space environmental satellite testing chambers. Boeing has indicated that these facilities have the volume to test a complete fabrication equipment setup at LEO pressures for the times needed to complete a multilevel structure. Such tests would verify such equipment questions as proper chamber design, gas flows needed during deposition, wafer handling robotics and power usage.

List of Figures and Graphics

References

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Figure 1

Microfabrication Process Steps

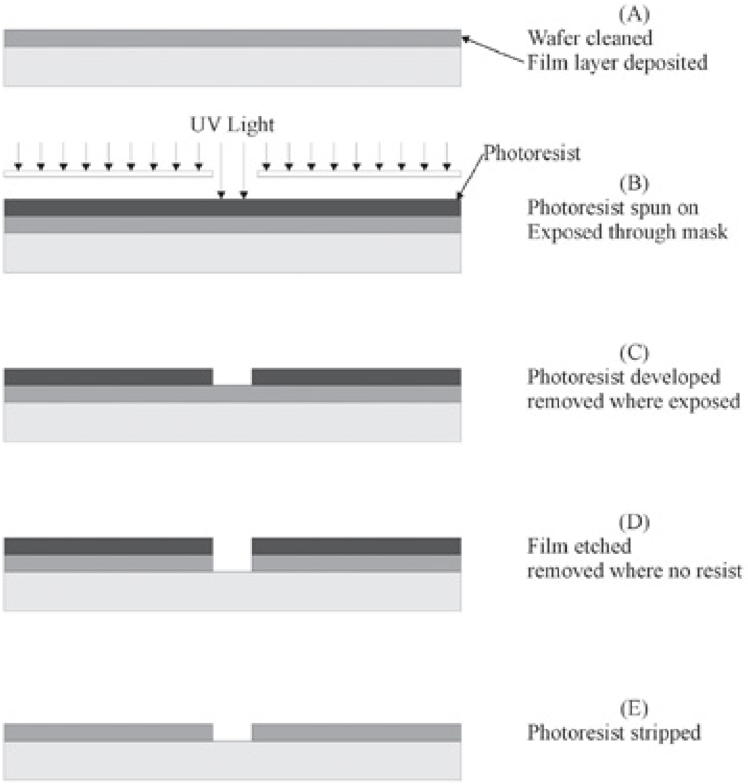
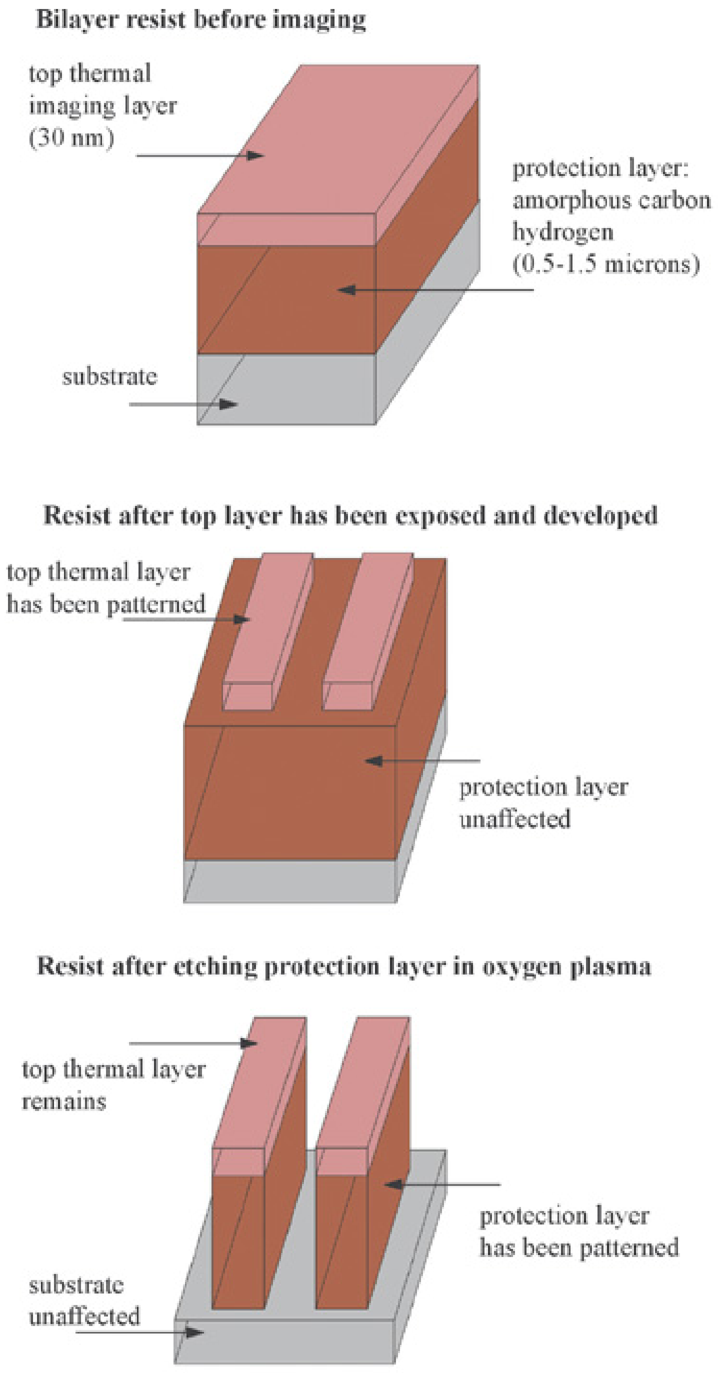


Figure 2



Thermal Inorganic Resist

Figure 3

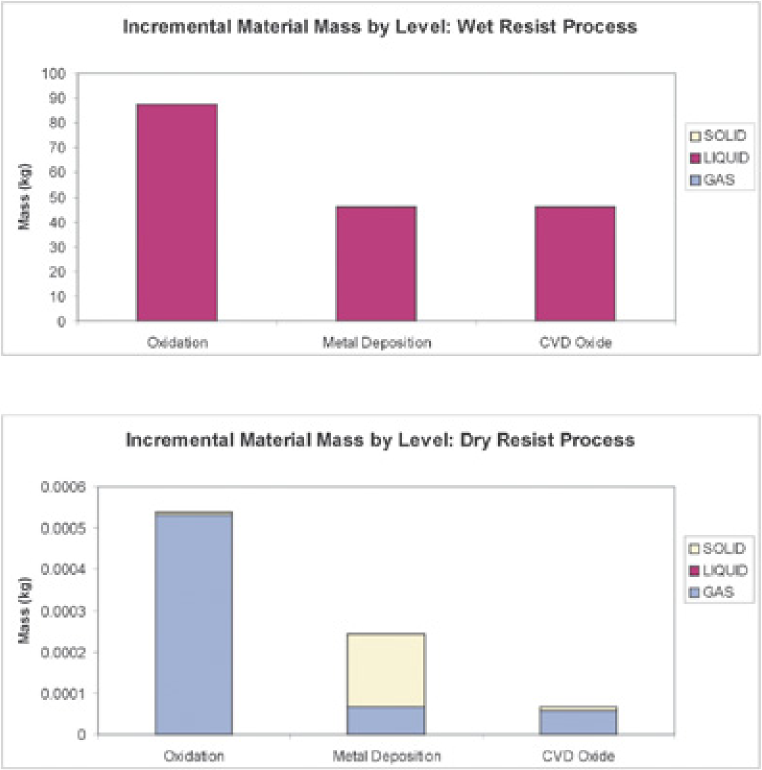

Incremental Material Mass by Level: Wet Resist Process
Mass (kg)
100
90
80
70
60
50
40
30
20
10
0
Oxidation
Metal Deposition
CVD Oxide
SOLID
LIQUID
GAS
Incremental Material Mass by Level: Dry Resist Process
Mass (kg)
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
Oxidation
Metal Deposition
CVD Oxide
SOLID
LIQUID
GAS

Figure 4

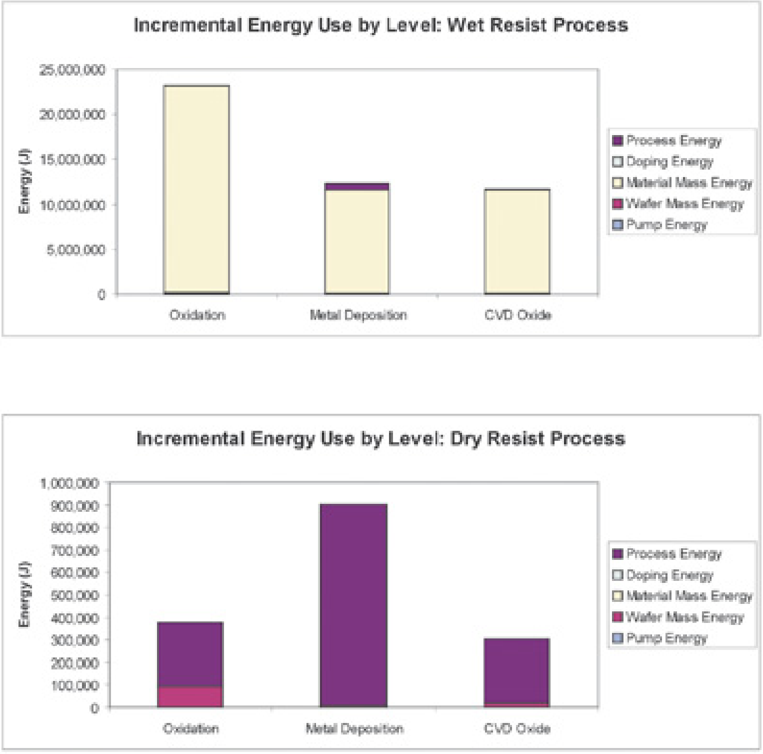
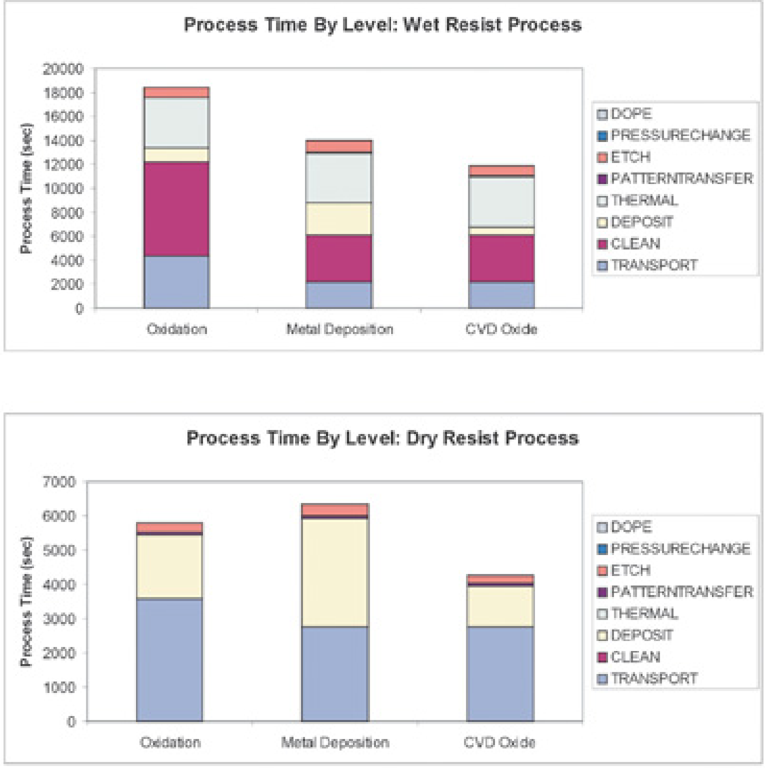

Incremental Energy Use by Level: Wet Resist Process
Energy (J)
25,000,000
20,000,000
15,000,000
10,000,000
5,000,000
0
Oxidation
Metal Deposition
CVD Oxide
Process Energy
Doping Energy
Material Mass Energy
Wafer Mass Energy
Pump Energy
Incremental Energy Use by Level: Dry Resist Process
Energy (J)
1,000,000
900,000
800,000
700,000
600,000
500,000
400,000
300,000
200,000
100,000
0
Oxidation
Metal Deposition
CVD Oxide
Process Energy
Doping Energy
Material Mass Energy
Wafer Mass Energy
Pump Energy

Figure 5


Process Time By Level: Wet Resist Process
Process Time (sec)
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
Oxidation
Metal Deposition
CVD Oxide
DOPE
PRESSURECHANGE
ETCH
PATTERNTRANSFER
THERMAL
DEPOSIT
CLEAN
TRANSPORT
Process Time By Level: Dry Resist Process
Process Time (sec)
7000
6000
5000
4000
3000
2000
1000
0
Oxidation
Metal Deposition
CVD Oxide
DOPE
PRESSURECHANGE
ETCH
PATTERNTRANSFER
THERMAL
DEPOSIT
CLEAN
TRANSPORT